

Article

Sustainability Assessment of Green Concrete Using Building Material Sustainability Potential (BMSP) and Empathetic Added Sustainability Index (EASI)

Rosalia Ruiz-Ruiz ^{1,2,*}, Elia Mercedes Alonso-Guzman ^{2,*}, Hugo L. Chavez-Garcia ²,
Marco Antonio Navarrete-Seras ², Mauricio Arreola-Sánchez ², Judith Alejandra Velazquez-Perez ^{1,2}
and Wilfrido Martinez-Molina ²

¹ Doctoral Program in Civil Engineering, Faculty of Civil Engineering, Universidad Michoacana de San Nicolás de Hidalgo, Morelia 58070, Mexico

² Faculty of Civil Engineering, Universidad Michoacana de San Nicolás de Hidalgo, Morelia 58070, Mexico; mnavarrete@umich.mx (M.A.N.-S.); mauricio.arreola@umich.mx (M.A.-S.); wilfrido.martinez@umich.mx (W.M.-M.)

* Correspondence: rosalia.ruiz@umich.mx (R.R.-R.); elia.alonso@umich.mx (E.M.A.-G.)

Abstract

Concrete remains the most widely used construction material owing to its affordability, local availability, mechanical performance, durability, and versatility. However, its production has a significant environmental impact, and its service life may be reduced under aggressive exposure conditions, affecting both the functionality and cost of structures. This study presents a sustainability assessment based on a harmonized database of previously developed concrete mixtures, rather than a new experimental campaign. Waste-containing mixtures and their corresponding conventional or reference controls were considered to anchor the comparison to reference concretes, rather than only to the minimum values within the analyzed dataset. The objective was to compare the consistency among sustainability index formulations: K_{SB} and $K_{SB,C}$, associated with the Building Material Sustainability Potential (BMSP), and the Empathetic Added Sustainability Index (EASI). These formulations integrate functional and environmental performance, although they differ in their aggregation approach and in the treatment of economic variables, such as cost and eco-cost. The indicators considered include 28-day compressive strength, carbonation rate, global warming potential (GWP), gross energy requirement (GER), natural raw material consumption (NRM), eco-cost, and material cost. The results show that mixtures with higher replacement levels of natural aggregates by recycled concrete aggregate and partial replacement of cement by locally sourced ashes exhibited the best integrated performance. The 300/100RCag mixture stood out, with index values close to 3.43, 3.52, and 3.99, up to approximately four times those of the control. Sensitivity and uncertainty analyses showed that the highest-ranked mixtures generally maintained favorable positions across assessment methods and under $\pm 20\%$ input variability, although some alternatives exhibited substantial method-dependent ranking changes. The results demonstrate that local waste materials can improve concrete sustainability; however, their benefits depend on waste type, conditioning requirements, functional performance, and the selected sustainability assessment method.



Academic Editor: Sha Liang

Received: 28 May 2026

Revised: 10 July 2026

Accepted: 12 July 2026

Published: 14 July 2026

Copyright: © 2026 by the authors.

Licensee MDPI, Basel, Switzerland.

This article is an open access article distributed under the terms and

conditions of the [Creative Commons](https://creativecommons.org/licenses/by/4.0/)

[Attribution \(CC BY\)](https://creativecommons.org/licenses/by/4.0/) license.

Keywords: green concrete; sustainability assessment; durability; life cycle assessment; recycled aggregates

1. Introduction

Concrete is the most widely used man-made material worldwide due to its great impact on construction because most structures designed to meet the demands of a constantly growing population (housing, transportation, energy, protection, among others) are made from it due to its availability, mechanical resistance, durability, versatility, fire resistance, among others [1–3]. According to the Global Cement and Concrete Association, the production of concrete worldwide in 2020 was 14 billion m³, 40% of which was for the residential market, while the production of cement, the main component of concrete, was 4.2 billion tons. The market value of both is \$440 billion [4]. Although concrete offers many benefits, it has a negative impact on the environment because cement production is responsible for 8% of global CO₂ emissions and consumes 14% of the industry's energy. Concrete production also requires the extraction of large amounts of raw materials and generates high emissions of suspended particles. Moreover, its sustainability is compromised by its lack of durability in aggressive exposure atmospheres, such as those in coastal and/or industrialized areas [2,5–7].

For this reason, academia and industry are constantly looking for alternatives that are more sustainable, such as green concrete, which is concrete in which at least one of its components is partially or completely replaced by another with a lower environmental impact, which is usually waste [8]. It can also refer to those specific types whose production does not lead to environmental destruction, and that have high performance and life cycle sustainability [9].

Green concretes can come in various forms, such as concretes with additions and substitutions of ash and other waste, ultra-high-performance concretes, geopolymers, concrete, lightweight concrete, nano concretes, among others [10]. On the one hand, there are works that incorporate ash, slag, fibers and supplementary cementitious materials (SCMs) as replacements for cementitious materials to improve the mechanical, environmental and durability performance of concrete, the most common additions being: fly ash (FA), sugar-cane bagasse ash (SCBA), ground granulated blast furnace slag (GGBFS), alkaline activated slag (AAS), micro silica and silica fume (SF) [11–22]. On the other hand, researchers have reported incorporating waste, mainly construction and demolition waste (C&DW), tires, polyethylene terephthalate (PET), ground glass, and slag, to avoid unnecessary extraction from quarries by replacing natural aggregates in concrete and, thus, reducing costs and environmental impacts [18,23–32].

Although sustainability is the integration of the social, economic, and environmental pillars, in the case of materials, a fourth pillar is usually added, that of functionality, which represents the technical requirements or features [33]. Although green concretes have emerged as alternatives in the search for sustainability, they are not necessarily more sustainable than conventional concrete, since the conditioning and transport of incorporated waste could have a great impact, so it is important to determine their sustainability levels [28]. In response to this, several proposals have emerged to determine the level of sustainability of these. Some researchers propose indices that evaluate some of the pillars of sustainability [30,34–36]. Others determine global indices that include processes of normalization, weighting, and aggregation of indicators from various pillars [14,15,18,19,21,29,37–39]; some even make use of multicriteria decision analysis (MCDA) [40,41]. For example, Gettu et al. [35] proposed two indices: the apathy index, which relates CO₂ emissions to the service life of the structure; and the energy intensity index related to the energy consumed and the mechanical strength of the concrete. Similarly, Václavík et al. [30] developed the $SUI_{\text{climate change}}$, $SUI_{\text{resources}}$, and SUI_{total} sustainability indices, which relate environmental parameters (climate change, damage to human health and the ecosystem, resource extraction and percentage of natural aggregates used) and technical concrete parameters

(compressive and freezing resistance). Hossain et al. [36] developed a model to determine social sustainability based on a social life cycle assessment (S-LCA), taking indicators such as producer responsibility, human resource management, community development, social development, corporate social responsibility and environmental responsibility, which involve all actors in the value chain. The global index known as the Building Material Sustainability Potential (BMSP) proposed by Mueller et al. [39] relates mechanical performance and durability to environmental impact through one indicator of each type; it uses parameters such as compressive strength, carbonation rate, resistance to freezing and thawing, chloride diffusion coefficient and global warming potential (GWP) that are normalized for calculation; and in some cases the cost and eco-cost are also included [14,15,18,20,42]. Coppola et al. [37] developed the empathic added sustainability index (EASI), which, unlike the BMSP, can include more than one environmental performance and durability indicator, depending on the function of the concrete, in addition to three environmental indicators being included in its determination. Coffetti et al. [29] made a modification to the EASI index so that it is applicable to materials that have a negative carbon footprint, such as carbon-sequestering aggregates. Based on multicriteria decision analysis, Shinkhede et al. [41] proposed the sustainability score (SS) for concrete, which integrates technical criteria (rapid chloride penetration, sorptivity, and density), economic criteria (product cost), environmental criteria (use of resources and pollution) and social criteria (compatibility and comfort), while Opon et al. [40] addressed the uncertainties associated with the method. Sirico et al. and Soltanzadeh et al. [19,21] proposed eco-mechanical indices, based on the integration of the ecological and mechanical indices, in which each one includes several parameters, such as compressive strength, tension, bending, fracture energy, GWP, acidification, ecotoxicity, resource depletion, water scarcity, among others. Although there are many proposals for sustainability indices, it has been identified that the following are necessary:

- To extend the environmental assessment to a life cycle assessment (LCA) from cradle to grave, or even from cradle to cradle;
- To include social indicators directly;
- To have general reference values for parameters;
- To establish relationships between methods and/or aggregation approaches, among others;
- To include uncertainty and sensitivity analyses.

As can be seen, there are several methods to determine the sustainability of green concretes, but there is a lot of variability in terms of the parameters used and how they are integrated, so the ranking of the mixtures determined using a certain index could be very different if it is calculated with another. This study contributes to the field of recycling and waste valorization by evaluating 28 concrete mixtures incorporating regionally abundant waste materials, including plastic waste, glass waste, recycled concrete aggregates, and industrial ashes. Through the application and comparison of two sustainability index calculation methods, this research assesses the potential of these wastes as partial substitutes for cementitious materials and/or virgin aggregates, as well as the consistency of the rankings obtained using different methods and with input parameter variations of $\pm 20\%$. In a region where the sustainability of concrete mixtures containing recycled materials is not usually determined, this study aims to provide evidence to support the selection of more sustainable mixtures and to promote circular economy strategies in the construction industry.

2. Results and Discussion

In this section, the indicator and index results for the study mixtures are presented using grouped bar charts according to the groups described in the methodology and a color

pattern based on the type of waste they contain. The colors are light blue (PET), dark blue (PET and ash), light gray (ash), dark gray (RCA and ash), and green (glass). In each group, the first bar corresponds to the control (concrete without additions), which corresponds to the reference value used for normalization. In the case of functional parameters, reference values (red lines) of the corresponding Mexican regulations have also been included. In addition, a sensitivity analysis by different weights and aggregation methods is included.

2.1. Functional, Environmental and Economic Indicators

Figures 1 and 2 show the results of the functional indicators of the green concretes of this study. Figure 1 shows that more than half of the mixes meet the specified 28-day strength according to NMX-C-083-ONNCCE-2014; even mixes with ash substitutions and recycled concrete aggregates (300/100RCAg, 300/10BA, 300/100RCAg/10BA, 300/10SCBA, 300/100RCAg/10SCBA, 180/100RCAg/10SCBA, 180/10SCBA) exceed the benchmark by between 15% and 47%. However, it can also be noted that, in most mixtures with plastic waste additions (PET, PETc, PP), the resistance decreases as the percentage of addition increases. This decrease in resistance becomes even greater when 15% SCBA is added, as in the case of 330/0.8PETc + 15SCBA, in which the decrease was 26% with respect to its control. Although there are several authors who have found that the use of SCBA as a substitute for cement increases compressive strength, replacements greater than 20% exhibit the opposite effect [43,44]. On the other hand, Coviello et al., Cárdenas-Pulido et al., and Khatab et al. [45–47] found that the loss of compressive strength of concretes containing PET fibers is due to the surface texture of the plastic and the dimensions of the fiber, together with the weakness of the internal structure of the concrete.

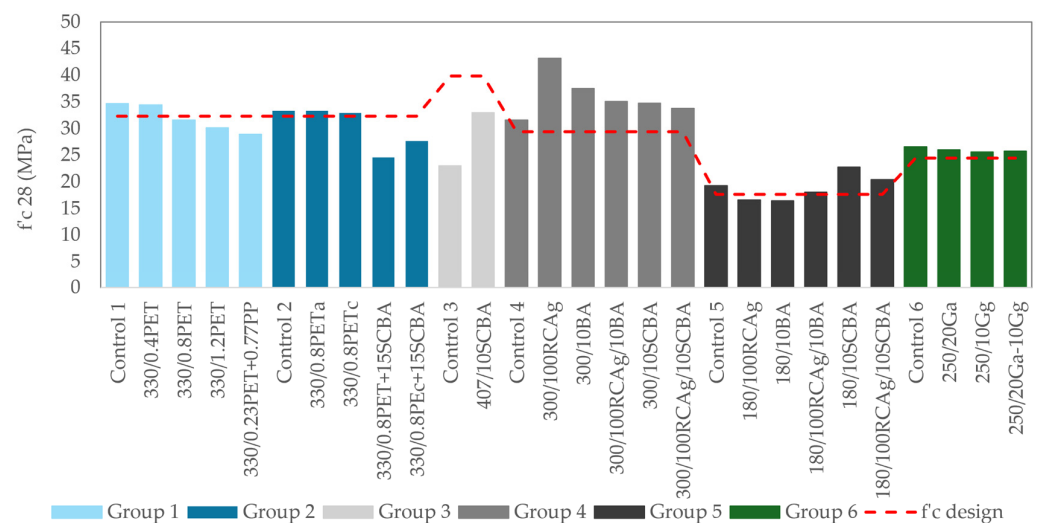


Figure 1. Compressive strength at 28 days for green concrete [48–55].

In the case of the carbonation rate, it is sought to be as small as possible to avoid durability problems, so that the NMX-C-515-ONNCCE-2016 [56] establishes that values lower than $3 \text{ mm/y}^{1/2}$ correspond to concretes with high resistance to carbonation, such is the case of most mixtures with ash substitutions and/or recycled concrete aggregates, the rest are considered with average strength ($3 \text{ mm/y}^{1/2} \leq \text{KCO}_2 \leq 6 \text{ mm/y}^{1/2}$), except for the PR-0.8+CBC15 mixture which is considered poor concrete.

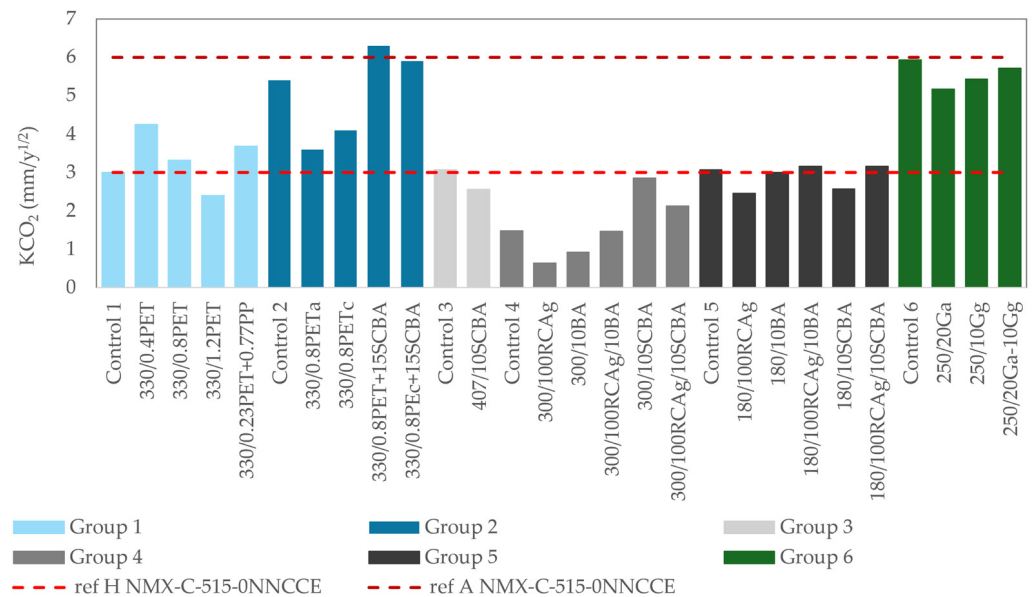


Figure 2. Carbonation rate for green concrete [48–55].

Figures 3 and 4 show the environmental indicators gross energy requirement (GER) and global warming potential (GWP) that were determined using the life cycle assessment (LCA) methodology. Figure 3 shows that the lowest energy demand (≈ 1500 MJ/m³) corresponds to concretes with high proportions of replacement of natural aggregates by recycled ones, both by concrete and glass waste, whereas the highest values (≈ 3000 MJ/m³) are those with the addition and/or substitution of waste whose conditioning operations demand more energy, as in the case of SCBA, which caused 15–60% increases in GER in the 300/10SCBA and 330/0.8PETc + 15SCBA mixtures compared with their controls. In addition, this effect is consistent with the GWP increases shown in Figure 4. Ravindra et al. [35] reported energy consumed between 2000 MJ/m³ and 3000 MJ/m³ for green concretes, with the lowest demands for concretes with slag, ternary, and with Limestone Calcined Clay Cement (LC3). With respect to emissions, the mixtures studied by Liu et al. and Coffetti et al. [20,29] generate between -479 kg CO₂ eq and 468 kg CO₂ eq, with negative values for concretes made with carbon-sequestering aggregates.

The eco-costs of all the mixtures with residues evaluated are lower than those of their respective controls, as can be seen in Figure 5. This decrease depends on the amount of Portland cement, as well as the type of waste that is added to the mix and the final disposal avoided by reusing it. That is why the lowest values correspond to concrete with a high water/cementitious ratio (W/C), made with ash and/or recycled aggregates (RCA or glass) as a replacement for PC and natural aggregates, as in the case of 180/100RCAG/10SCBA and 250/20Ga-10Gg, which reduce the eco-cost by 29% and 52% with respect to their reference.

The results of the natural raw material consumption (NRMCI) indicator are shown in Figure 6, in which most of the mixtures have a similar consumption of raw material (≈ 2000 kg/m³). However, this consumption is reduced by up to 47% in mixtures with partial replacement of PC by ash and total replacement of natural coarse aggregates by RCA, such as in 180/100RCAG, 180/100RCAG/10BA and 180/100RCAG/10SCBA.

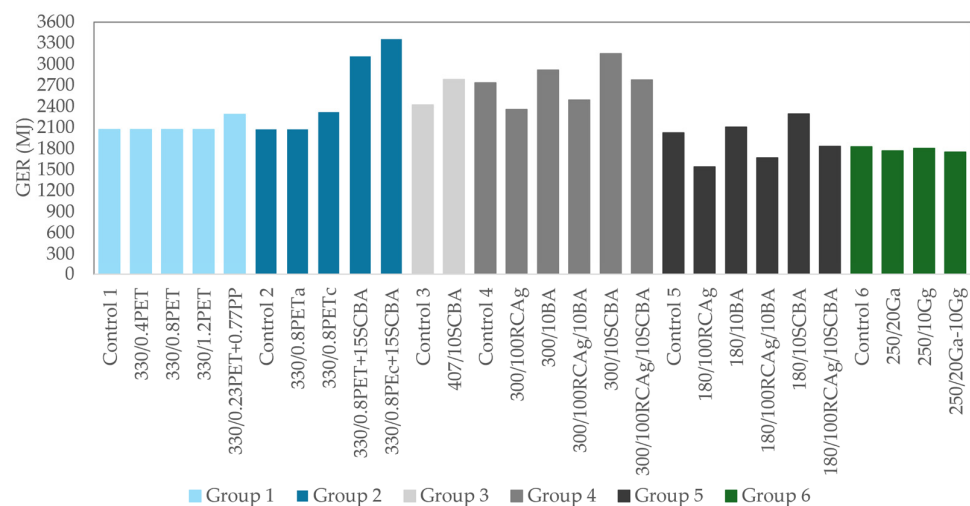


Figure 3. Gross energy requirement for 1 m³ of green concrete.

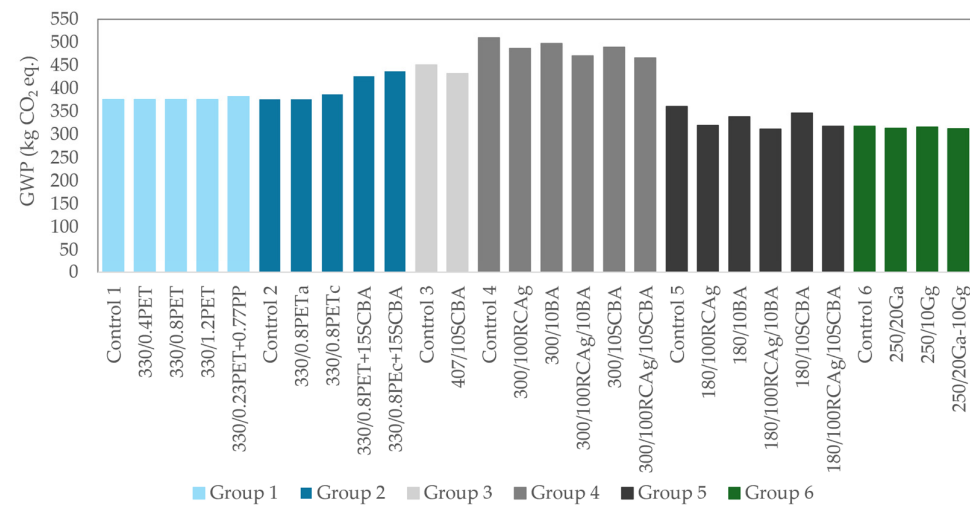


Figure 4. Global warming potential for 1 m³ of green concrete.

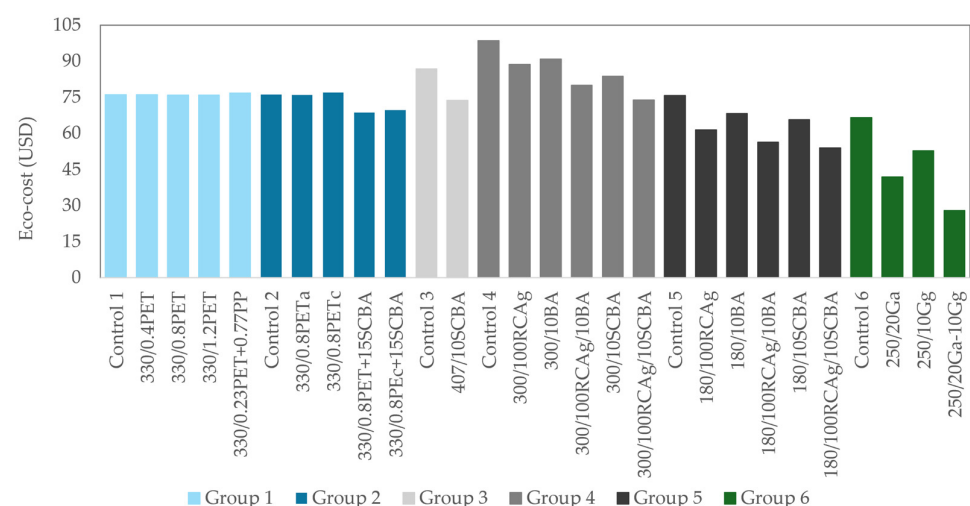


Figure 5. Eco-cost for 1 m³ of green concrete.

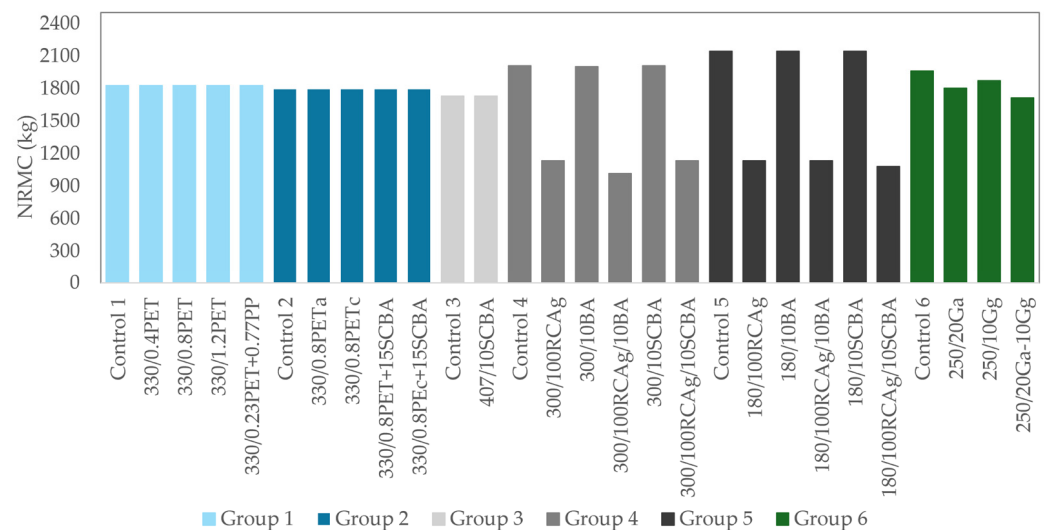


Figure 6. Natural raw material consumption for 1 m³ of green concrete.

Figure 7 shows that the most expensive green concretes are those in Group 4, which were designed with a lower W/C ratio because a greater amount of cement is needed (precisely the material with the highest cost). Commercial polypropylene (PP) fibers also come with a high price tag, so the mixture (330/0.23PET + 0.77PP) is also one of the most expensive. On the other hand, the lowest costs correspond to mixtures in Groups 5 and 6 that, in addition to having a low cement content, include the replacement of stone aggregates.

It can also be noted that, consistent with the literature, the cost is normally higher than the eco-cost per m³ of concrete in all cases [14,15].

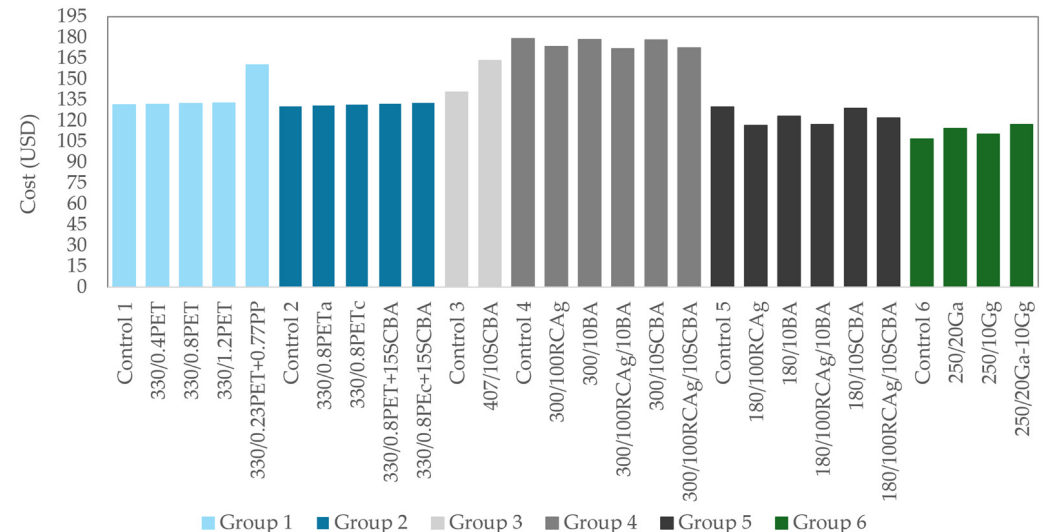


Figure 7. Cost for 1 m³ of green concrete.

2.2. Sustainability Indices

This section shows the results of the sustainability indices determined according to the functional, environmental, and economic indicators defined for this study.

On the one hand, the KSB and K_{SB,C} indices that refer to the sustainability potential of building materials (BMS_P), in this case green concretes, are presented in Figures 8 and 9. According to these indices, the mixtures with the greatest sustainability potential are 300/100RCAG (3.52), 300/10BA (2.07), and 407/10SCBA (2.02), which are 2 to 3 times more sustainable than their controls. In addition, they are superior to those reported by Hrabova et al. and Liu et al., who reported values between 1.07 and 2.67 for concrete

with ashes [14,20,57]. It can be noted that precisely the mixtures with the highest levels of sustainability were those in which the functional parameters stood out above the rest, together with the decrease in the consumption of natural raw materials due to the use of waste with low treatment.

In all cases, we see that the K_{SB} index is higher than $K_{SB,C}$, which includes mechanical performance, durability, and eco-cost parameters. But when environmental impact and cost are added instead of the latter, its value is reduced by up to 70% in some cases, while maintaining the sustainability position.

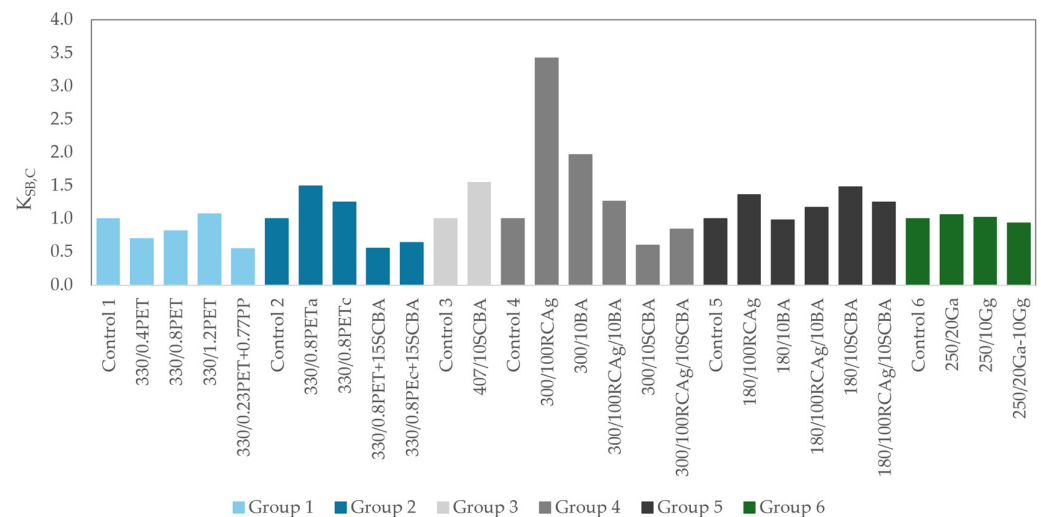


Figure 8. Building Material Sustainability Potential ($K_{SB,C}$) for 1 m³ of green concrete.

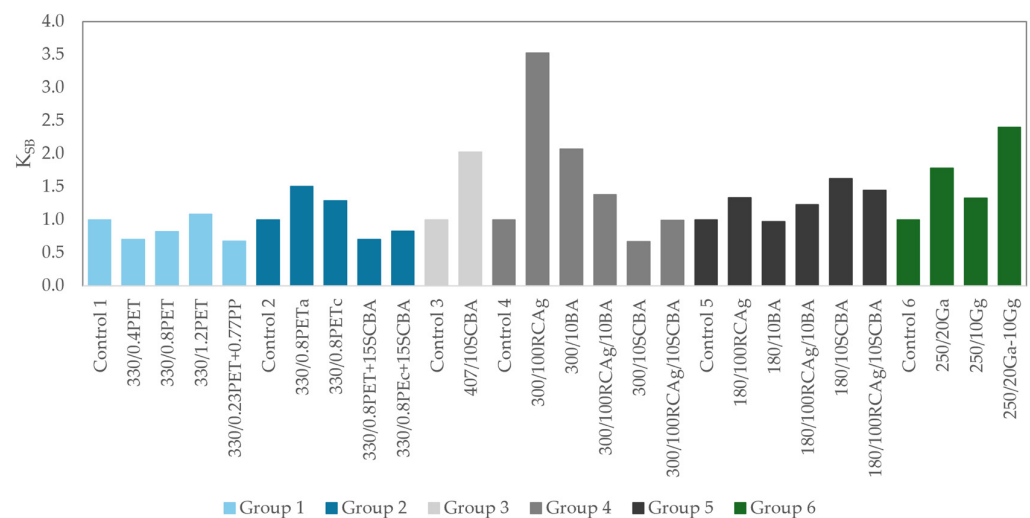


Figure 9. Building Material Sustainability Potential (K_{SB}) for 1 m³ of green concrete.

On the other hand, the results of the Empathic Added Sustainability Index (EASI) are shown in Figure 10. The concretes with the highest sustainability index are the same as those identified by the other indices, but with higher values, even higher than 3.36, which was the highest value reported by Coppola et al. [37].

Finally, in Figures 11–13, Pearson correlations among these indices are shown. In all cases, there is a good linear correlation (0.76–0.98). However, the EASI vs. $K_{SB,C}$ correlation (see Figure 12) has the highest coefficient of determination ($r^2 \approx 0.98$), as expected, given that both indices use the same type of indicators, except for cost.

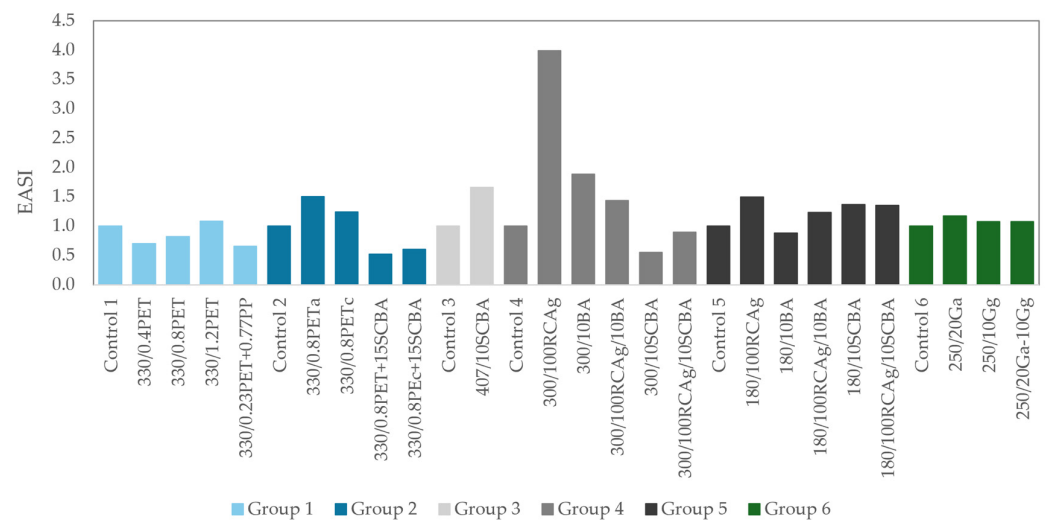


Figure 10. Empathetic Added Sustainability Index for 1 m³ of green concrete.

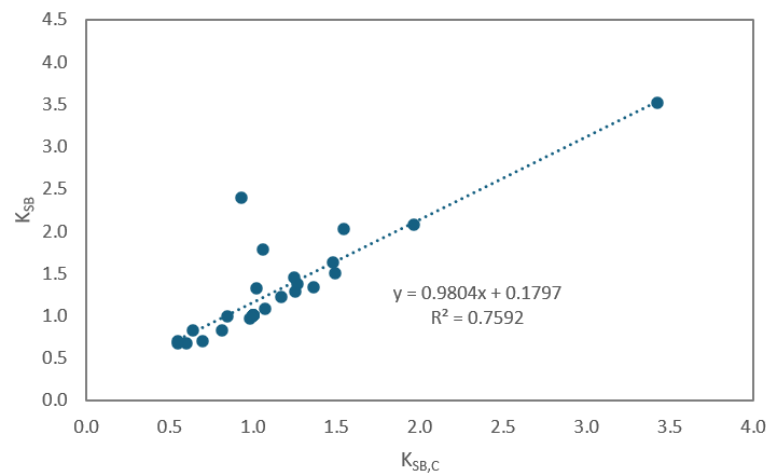


Figure 11. Correlation between K_{SB} and $K_{SB,C}$ for green concretes.

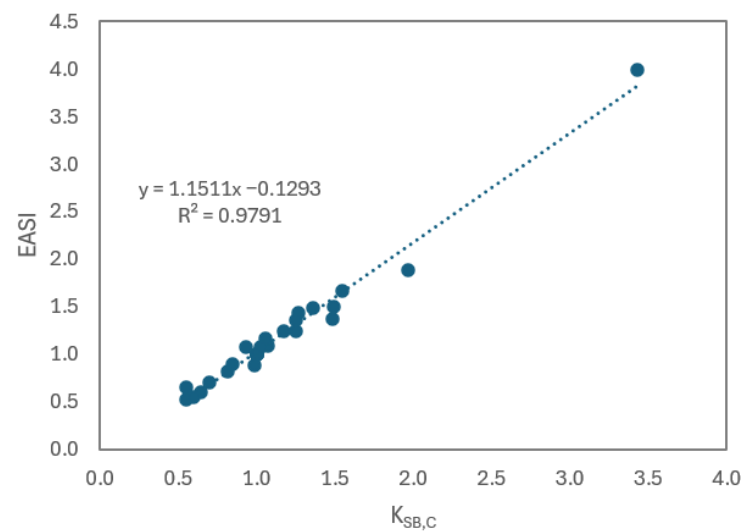


Figure 12. Correlation between EASI and $K_{SB,C}$ for green concretes.

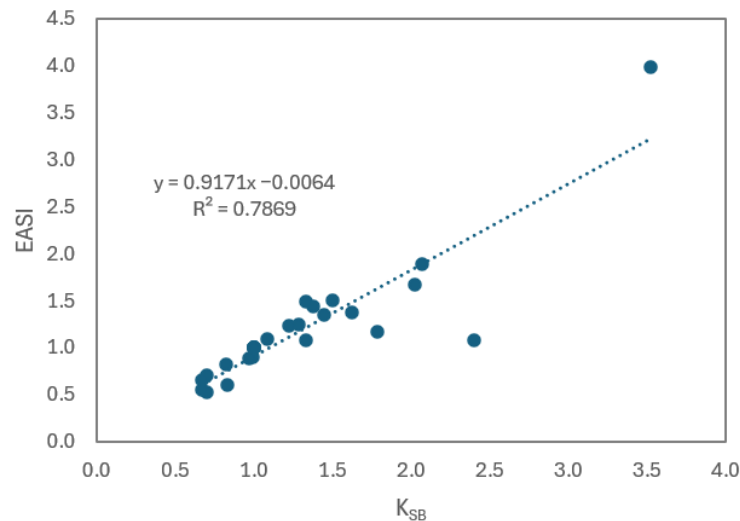


Figure 13. Correlation between EASI and K_{SB} for green concretes.

2.3. Uncertainty and Sensitivity Analysis

In this section, the results of the uncertainty and sensitivity analysis carried out on the sustainability indices of the study mixtures are presented.

Table 1 shows a sensitivity analysis based on the maximum change in sustainability position depending on the calculation method. Most of the mixtures, about 93%, have low or very low sensitivity to the method used; whereas the 250/20Ga and 250/20Ga-10Gg mixtures have moderate and high sensitivity, respectively. This suggests that, in general terms, K_{SB} , $K_{SB,C}$, and EASI produce a broadly consistent relative ordering, with the 300/100RCa mixture being the clearest example of methodological stability and the one with the best sustainability position. However, the variation of 19 positions in the 250/20Ga-10Gg mixture demonstrates that the perceived sustainability of some mixtures may depend strongly on the indicators included and the aggregation structure of the evaluation method.

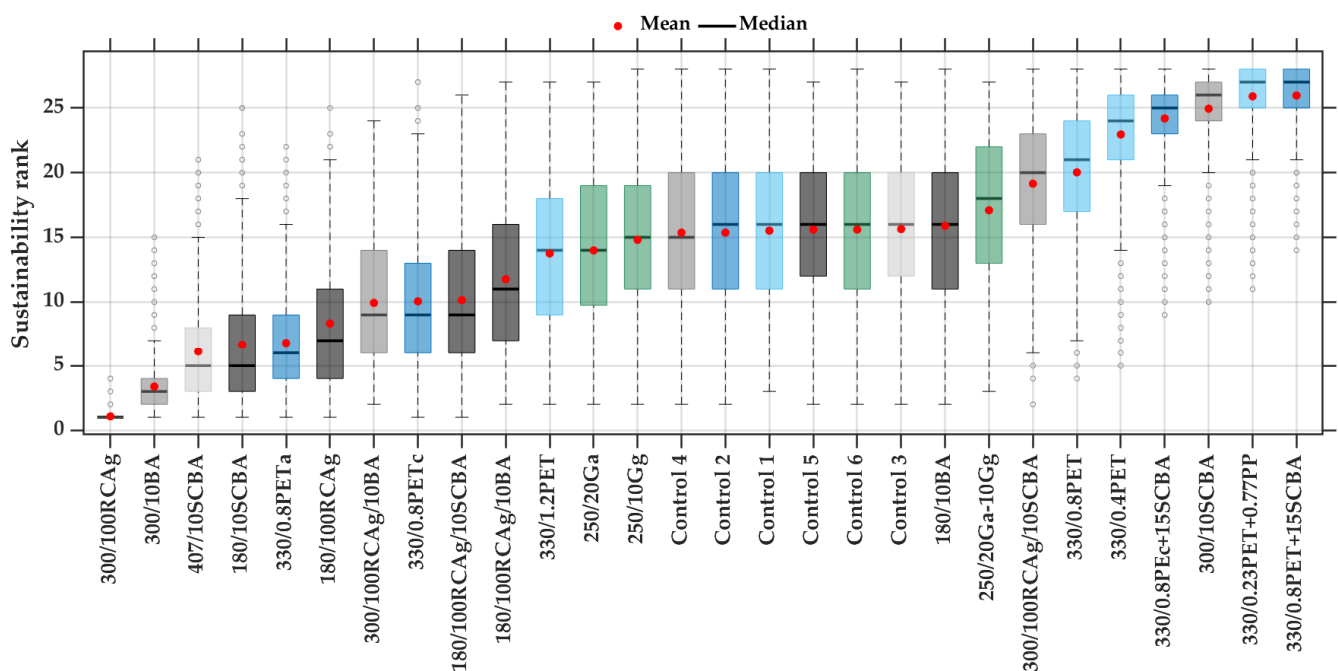
Figures 14–16 show the simulated sustainability rankings considering a variation of $\pm 20\%$ of the input parameters simultaneously. In general, it can be noted that regardless of the aggregation method, the least variability occurs in the extreme positions and that, in addition, the mixtures 300/100RCa, 300/10BA and 407/10SCBA remain in the top 5, that is, they remain robust mixtures, even with variation of the input data. However, blends in intermediate positions have a lot of variability, indicating greater uncertainty in the sustainability ranking. A special case is 250/20Ga-10Gg, which maintains highly favorable positions under K_{SB} but shifts toward intermediate or less favorable positions when the $K_{SB,C}$ and EASI indices are applied. Thus, although its ranking is relatively robust to input variability within K_{SB} , its sustainability classification is highly sensitive to the assessment methodology, which is also consistent with the sensitivity analysis of the indices without variation of input variables, as shown in Table 1. This result confirms that within-method robustness does not necessarily imply methodological robustness.

Table 1. Ranking sensitivity to the aggregation method for green concretes.

Mixture	Rank			Mean Rank	Mean Shift	Maximum Shift	Sensitivity
	$K_{SB,C}$	K_{SB}	EASI				
Control 1	14	15	15	15	1	1	Very low
330/0.4PET	24	26	24	25	1	2	Very low
330/0.8PET	23	24	23	23	1	1	Very low

Table 1. Cont.

Mixture	Rank			Mean Rank	Mean Shift	Maximum Shift	Sensitivity
	$K_{SB,C}$	K_{SB}	EASI				
330/1.2PET	11	14	12	12	2	3	Low
330/0.23PET + 0.77PP	28	27	25	27	2	3	Low
Control 2	14	15	15	15	1	1	Very low
330/0.8PETa	4	7	4	5	2	3	Low
330/0.8PETc	8	12	9	10	3	4	Low
330/0.8PET + 15SCBA	27	25	28	27	2	3	Low
330/0.8PETc + 15SCBA	25	23	26	25	2	3	Low
Control 3	14	15	15	15	1	1	Very low
407/10SCBA	3	4	3	3	1	1	Very low
Control 4	14	15	15	15	1	1	Very low
300/100RCag	1	1	1	1	0	0	Very low
300/10BA	2	3	2	2	1	1	Very low
300/100RCag/10BA	7	9	6	7	2	3	Low
300/10SCBA	26	28	27	27	1	2	Very low
300/100RCag/10SCBA	22	21	21	21	1	1	Very low
Control 5	14	15	15	15	1	1	Very low
180/100RCag	6	10	5	7	3	5	Low
180/10BA	20	22	22	21	1	2	Very low
180/100RCag/10BA	10	13	10	11	2	3	Low
180/10SCBA	5	6	7	6	1	2	Very low
180/100RCag/10SCBA	9	8	8	8	1	1	Very low
Control 6	14	15	15	15	1	1	Very low
250/20Ga	12	5	11	9	5	7	Moderate
250/10Gg	13	11	13	12	1	2	Very low
250/20Ga-10Gg	21	2	14	12	13	19	High

Figure 14. Monte Carlo distribution of sustainability rank for green concretes, based on $K_{SB,C}$.

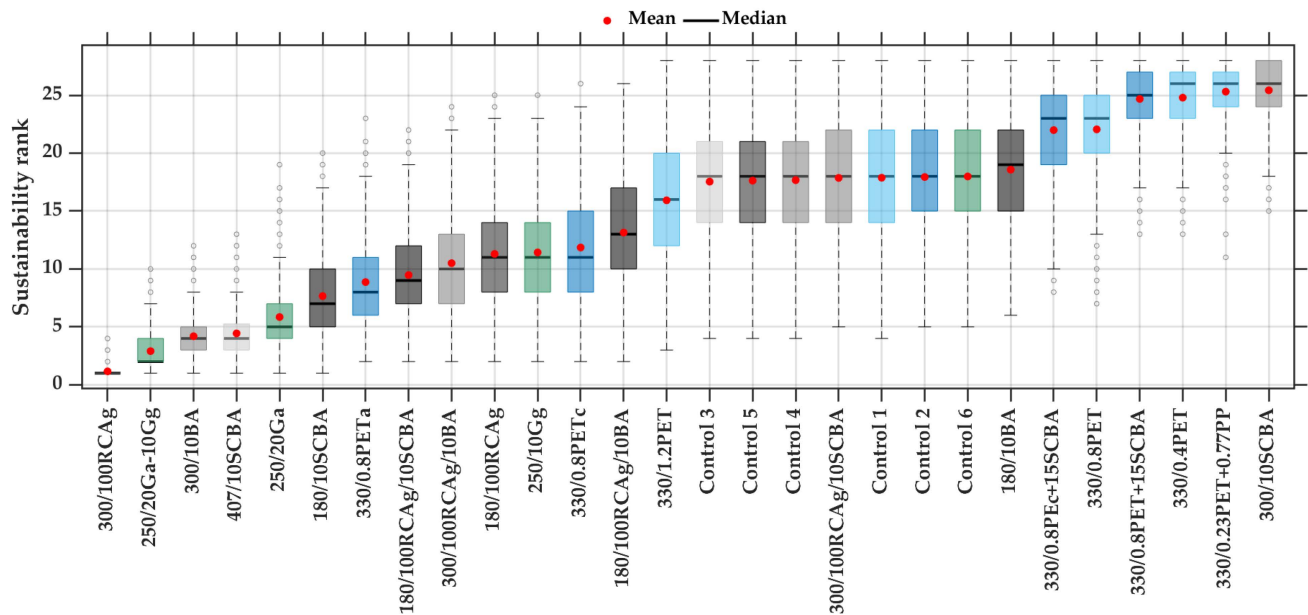


Figure 15. Monte Carlo distribution of sustainability rank for green concretes, based on K_{SB} .

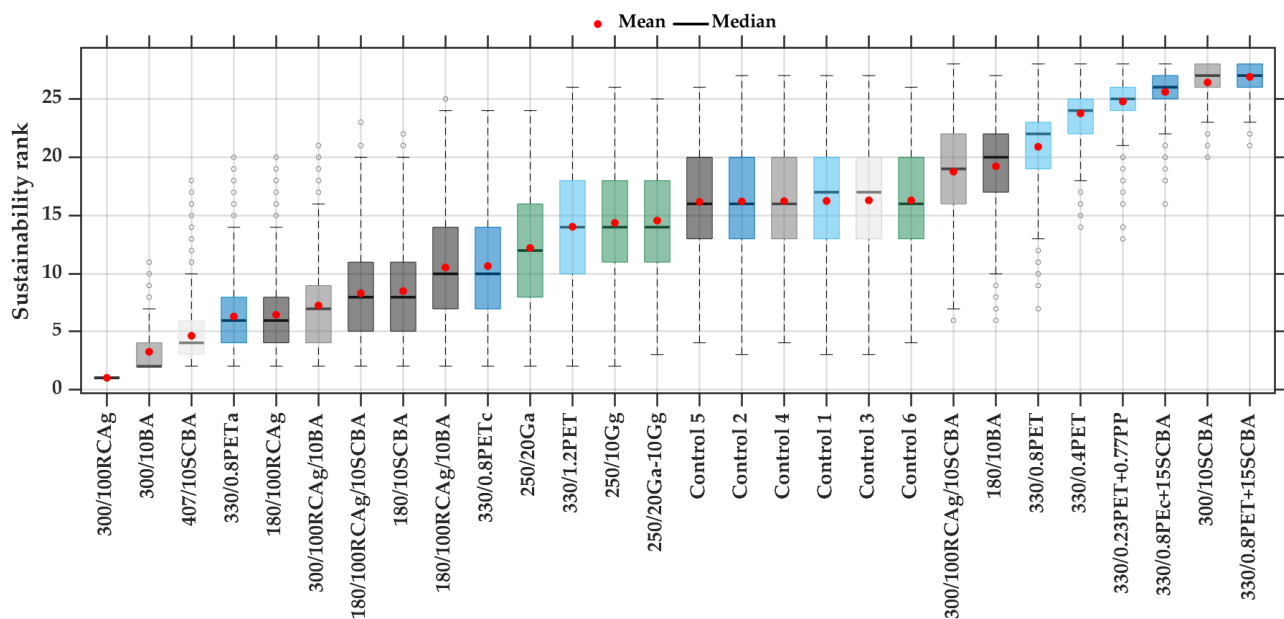


Figure 16. Monte Carlo distribution of sustainability rank for green concretes, based on EASI.

3. Materials and Methods

3.1. Materials

The object of this work is to compare, using different indices, the sustainability of green concretes made with supplementary materials (SCM) and/or locally generated waste, which were designed and manufactured in the Materials Laboratory “Ing. Luis Silva Ruelas”, in Morelia, Mexico, during the last decade, to reduce the environmental impacts and costs associated with their production without compromising their functionality.

The mixtures under study were grouped into the following:

- Group 1: concretes made with natural aggregates and Portland cement (CP), with additions of laboratory-made PET fibers and commercial polypropylene (PP) based on the cement mass [48–50].

- Group 2: concretes made from natural aggregates, CP, laboratory-made PET fiber additions, commercial PET flakes, and sugarcane bagasse ash (SCBA) based on cement mass [51].
- Group 3: concrete made with natural aggregates and CP partially replaced by 15% SCBA [52].
- Group 4: low water/cementitious (W/C) concrete, made with natural aggregates and CP, with total replacement of the coarse aggregate by recycled concrete aggregate (RCA) and partial substitution with SCBA and brick processing ash (CH) [53,54].
- Group 5: high W/C ratio concretes, made with natural aggregates and CP, total replacement of coarse aggregate with RCA and partial substitutions of SCBA and CH [53,54].
- Group 6: concretes made with natural aggregates and CP, with partial replacement of the fine and coarse aggregates by glass waste [55].

The nomenclature, design, provision, and descriptions of the component materials of the mixtures studied are shown in Table 2.

Table 2. Mixture design and material consumption for 1 m³ of green concrete [48–55].

Mixture	f'c (MPa)	W/C Ratio	Materials (kg)													Water
			Cementing & Fibers							Aggregates						
			PC	PET	PETg	PP	SCBA	BA	S1	S2	S3	G1	G2	G3		
Control 1	32	0.51	402							293	293		983			260
330/0.4PET	32	0.51	402	1.6						293	293		983			260
330/0.8PET	32	0.51	402	3.2						293	293		983			260
330/1.2PET	32	0.51	402	4.8						293	293		983			260
330/0.23PET + 0.77PP	32	0.51	402	0.7		2.5				293	293		983			260
Control 2			402							513			1012			267
330/0.8PETa	32	0.51	402	3.2						513			1012			267
330/0.8PETc	32	0.51	402		3.2					513			1012			267
330/0.8PET + 15SCBA	32	0.51	402	3.2			60			513			1012			267
330/0.8PETc + 15SCBA	32	0.51	402		3.2		60			513			1012			267
Control 3	40	0.42	488								679		800			253
407/10SCBA	40	0.42	440				49				679		800			253
Control 4	29	0.45	552								730		985			298
300/100RCAg	29	0.45	552								815			858		320
300/10BA	29	0.45	524						28		730		985			290
300/100RCAg/10BA	29	0.45	524						28		730			985		290
300/10SCBA	29	0.45	498				56				730		985			298
300/100RCAg/10SCBA	29	0.45	498				56				815			858		320
Control 5	18	0.65	382								790		1060			294
180/100RCAg	18	0.65	363								815			858		320
180/10BA	18	0.65	345						19		790		1060			294
180/100RCAg/10BA	18	0.65	345						19		815			858		320
180/10SCBA	18	0.65	345				37				790		1060			294
180/100RCAg/10SCBA	18	0.65	345				37				790			1060		294
Control 6	25	0.62	331								800		898			266
250/20Ga	25	0.62	331								640	160	898			266
250/10Gg	25	0.62	331								800		808		90	266
250/20Ga-10Gg	25	0.62	331								640	160	808		90	266

PC: Portland cement CPC 30R RS, PET: PET macrofiber produced in the post-consumer bottle laboratory, PP: Commercial PP fiber SLTK microfiber 600, PETc: Ground PET from local recycler, SCBA: Sugarcane bagasse ash from the “Lázaro, Cárdenas” sugar mill, BA: Ash from local brick kilns, S1: River sand from the bank “El Coro”, S2: Volcanic sand from “La Unión” quarry, S3: Ground glass, G1: Crushed gravel from the quarry “La Roka”, G2: Recycled gravel from concrete demolition, G3: Crushed glass.

3.2. Sustainability Indexes

The green concretes were compared using the Building Material Sustainability Potential (BMSP) and Empathetic Added Sustainability Index (EASI) indices because the indicators comprising them can be calculated using information available for the selected mixtures, and they are also parameters that are usually considered in regulations.

The comparison of the indices across the different mixtures seeks to determine whether the sustainability ranking remains consistent.

The first method, BMSP, was proposed by Mueller et al. [39], and it is made up of 3 variables: mechanical behavior (R), service life (L), and eco-cost (E), although in some works the cost (C) is added [14,15,42]. In this study, the standardized versions as in the work of Hrabová et al. [14] using Equations (1) and (2):

$$k_{SB} = \frac{\frac{f'c_{28}}{f'c_{28,ref}} \cdot 1 / \frac{KCO_2}{KCO_{2,ref}}}{\frac{Eco-cost}{Eco-cost_{ref}}} \quad (1)$$

$$k_{SB,C} = \frac{\frac{f'c_{28}}{f'c_{28,ref}} \cdot 1 / \frac{KCO_2}{KCO_{2,ref}}}{\frac{GWP}{GWP_{ref}} \cdot \frac{C}{C_{ref}}} \quad (2)$$

where

$f'c_{28}$ = compressive strength at 28 days (MPa).

KCO_2 = carbonation rate (mm/y^{1/2}).

Eco-cost = eco-cost (USD).

C = cost (USD).

ref = reference.

The second method, the EASI index proposed by Coppola et al. [37], relates the mechanical performance and durability of mixtures to 3 environmental parameters: natural raw material consumption (NRMC), energy consumption (GER), and GWP. As in the previous case, its normalized version was applied using Equation (3):

$$EASI = \frac{3 \cdot \frac{f'c_{28}}{f'c_{28,ref}} \cdot \frac{1}{\frac{KCO_2}{KCO_{2,ref}}}}{\frac{GER}{GER_{ref}} + \frac{GWP}{GWP_{ref}} + \frac{NRMC}{NRMC_{ref}}} \quad (3)$$

where

$f'c_{28}$ = compressive strength at 28 days (MPa).

KCO_2 = carbonation rate (mm/year^{1/2}).

GER = gross energy requirement.

GWP = global warming potential (kg CO₂ eq.).

NRMC = natural raw material consumption (kg).

ref = reference.

All indicators should be normalized with reference values that usually correspond to the control. Then, the value of the index (KSB, KSB,C and EASI) will be dimensionless, and the higher its value, the higher the level of sustainability of the concrete [15,18,29,37,38,42].

The following sections describe how the indicators and reference values used in this research were obtained.

3.2.1. Functional Indicators

Compressive strength was selected as the mechanical performance parameter, since it is the type of mechanical stress at which concrete mainly works and it is also the one that is regulated in Mexico. Although the durability of concrete depends on many factors, the carbonation rate was selected as the indicator for calculating the sustainability indices because the exposure environment at the study site corresponds to the rural/urban (C3) category. According to the classification of the Mexican durability regulations, they are concrete with moderate relative humidity of between 50% and 80% and CO₂ and SO₂ contamination; therefore, corrosion is induced by carbonation [58,59].

The 28-day compressive strength and carbonation rate, determined in accordance with the Mexican standards NMX-C-083-ONNCCE-2014 [60] and NMX-C-515-ONNCCE-2016 [56], were used as indicators of mechanical performance and service life, respectively.

The compressive strength was determined in cylindrical specimens of 10 cm in diameter and 20 cm in height, while the carbonation rate was determined in 10 cm diameter slices of 5 cm in height. Each trial was performed in triplicate, so the values reported in this study correspond to the average value of each mixture [48–55]. Then, the parameters were normalized with respect to the control of each group of mixtures.

3.2.2. Environmental Indicators

The GER and GWP environmental indicators were calculated using a cradle-to-gate life cycle assessment (LCA) for the production of one m^3 of concrete, as suggested by several researchers [15,18,38,39], using the Ecoinvent 3.0 database and the Sima Pro-8.2.3 software. The sub-processes contemplated are the production of materials, conditioning of waste to be used in the production of concrete, transport of materials and waste to the concrete production site; the production of concrete in laboratory conditions (mixed) and the final disposal avoided due to the use of waste in a new production chain. Waste materials were considered burden-free with respect to their previous life cycle, whereas the environmental burdens associated with the conditioning processes required for their incorporation into concrete, including the operations of size reduction (shredding, crushing and/or grinding), drying and sorting, were included. Thus, the modeling framework combined a cut-off logic at waste generation with an avoided-disposal credit. Figure 17 presents a schematic of the limits of the proposed product system for the LCA of the green concretes under study. All sub-processes are associated with the consumption of materials and energy, as well as transport. Material consumption is compiled in Table 2, while transportation and energy were calculated from the information reported for the life cycle inventory.

In an LCA, transport corresponds to the amount of material that is transported a certain distance by a certain type of vehicle and is measured in ton-kilometers (tkm) [28]. In this study, transportation includes the transfer of each of the materials and/or waste to the concrete production site, while the energy corresponds to that used in the conditioning of waste and the production of concrete under laboratory conditions.

Table 3 shows the Ecoinvent 3.0 models that were used to compile the LCI of most of the sub-processes to produce 1 m^3 of concrete, in addition to those created by the author of this work for the cases in which there was no compatible model. The latter correspond to processes for locally generated waste, for which models were created from the energy consumption of the conditioning operations to be used in concrete, such as selection, drying, crushing, and screening.

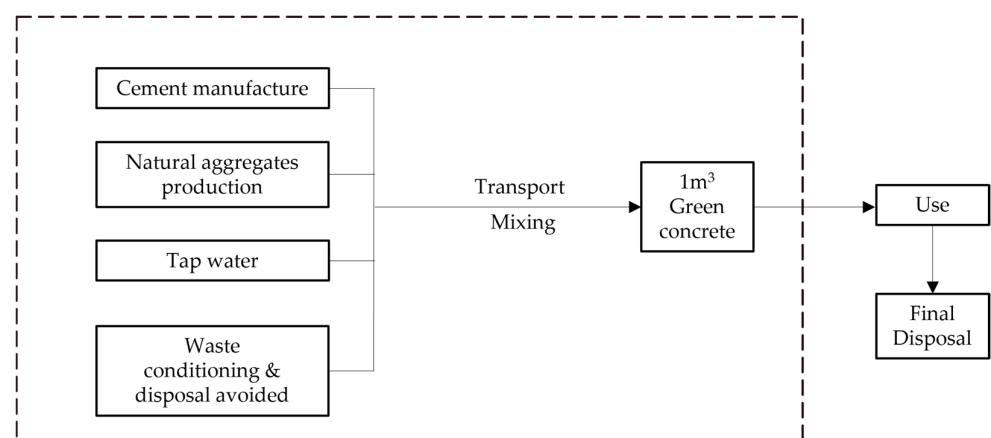


Figure 17. System boundary of LCA for 1 m^3 of green concrete.

Once the models were defined, the GER and GWP impact categories were calculated using the IPPC GWP 100a and Cumulative Energy Demand methods contained in Sima Pro-8.2.3, which correspond to the indicators required to determine the sustainability indices.

However, the NRMC environmental indicator is not calculated from an LCA, but as the sum of all non-renewable natural resources used to make concrete, such as water and aggregates [37].

Finally, eco-cost refers to the amount that could be spent to reduce environmental impact to a sustainable level [14]. In this study, it is calculated from the Design 4 sustainability database used in the design of products and/or processes with lower environmental impact. The models and their unit values are shown in Table 4, which were applied to the life cycle sub-processes to produce 1 m³ of green concrete.

Table 3. Ecoinvent 3.0 models for green concrete LCI.

Process	Model	Unit	Geographic Location
Materials			
CP	Cement, alternative constituents 6–20% {RoW} market for Alloc Def, U	kg	RoW
PET	_PET_fiber	kg	MX
PETc	Polyethylene terephthalate (PET), granulate, production mix, at plan, amorphous RER	kg	
PP_fiber	Polypropylene fibers (PP), crude oil based, production mix, at plant	kg	
SCBA-1 *	_Sugarcane bagasse ash (SCBA-1) conditioned for cementitious material	kg	MX
SCBA-2 *	_Sugarcane bagasse ash (SCBA-1) conditioned for cementitious material	kg	MX
SCBA-3 *	_Sugarcane bagasse ash (SCBA-1) conditioned for cementitious material	kg	MX
BA *	_Brick kiln ash (CH) conditioned for cementitious material	kg	MX
Water	Tap water {RoW} market for Alloc Def, U	kg	RoW
S1	Sand {GLO} market for Alloc Def, U	kg	GLO
S2	Sand {GLO} market for Alloc Def, U	kg	GLO
S3 *	_Ground glass conditioned for use as fine aggregate	kg	MX
G1	Gravel, crushed {GLO} market for Alloc Def, U	kg	GLO
G2 *	_recycled gravel, in-plant production in Mexico	kg	MX
G3 *	_Crushed glass conditioned for use as coarse aggregate	kg	MX
Transport			
Light-duty	Transport, freight, lorry 3.5–7.5 metric ton, EURO6 Alloc Def, U	tkm	RoW
Medium-duty	Transport, freight, lorry 7.5–16 metric ton, EURO3 Alloc Def, U	tkm	RoW
Heavy-duty	Transport, freight, lorry 16–32 metric ton, EURO5 Alloc Def, U	tkm	RoW
Production			
Electricity	Electricity, medium voltage {MX} market for Alloc Def, U	kWh	MX
Final disposal			
Concrete waste	Waste reinforced concrete {CH} treatment of, collection for final disposal Alloc Def, U	kg	CH
Ash	Average incineration residue {RoW} treatment of, residual material landfill Alloc Def, U	kg	RoW
Plastics	Inert waste {RoW} treatment of, sanitary landfill Alloc Def, U	kg	RoW
Glass	Landfill of glass/inert waste	kg	EU-27

* Models created by the author of this research work. The abbreviations for geographic location are RoW (Rest of the World), GLO (Global), CH (Switzerland), EU-27 (European Union), and MX (Mexico).

Table 4. Models used to determine the eco-cost of 1 m³ of green concrete.

Model	Eco-Cost (€)
Portland cement (kg)	0.1090
Sand (kg)	0.0070
Gravel (kg)	0.0070
Recycled gravel (kg)	0.0020
PET, recycled (estimate) (kg)	0.2120
PP, recycled (estimate) (kg)	0.2400
Transport, lorry 16–32 t, EURO5/RER S (tkm)	0.0310
Transport, lorry 7.5–16 t, EURO3/RER S (tkm)	0.0480
Transport, lorry 3.5–7.5 t, EURO5/RER S (tkm)	0.0890
Electricity general (kWh)	0.0070
Heavy fuel oil (excluding combustion) (L)	1.1220
Concrete, 5% water, to inert material landfill/CH S (kg)	0.0020
Plastics, mixture, 15.3% water, to sanitary landfill/CH S (kg)	0.0320
Average incineration residue, 0% water, to residual material landfill/CH S (kg)	0.5660
Landfill (kg)	0.1180

3.2.3. Economic Indicators

The economic indicator used in this research was cost, calculated as the sum of the cost of all materials and/or waste, based on the prices of local suppliers, as suggested in several works [6,15,20,61].

3.3. Uncertainty and Sensitivity Analysis

A two-stage sensitivity analysis was conducted to evaluate the reliability of the sustainability ranking of the 28 concrete mixtures. Composite indicators may be influenced by methodological choices and uncertainty in the input data; therefore, sensitivity and uncertainty analyses are recommended to assess the robustness of the resulting rankings [62].

First, methodological sensitivity was evaluated by comparing the rankings obtained using the K_{SB} , $K_{SB,C}$, and EASI sustainability assessment methods. For each method, the mixtures were ranked in descending order of their sustainability index, with rank 1 assigned to the best-performing mixture. Ranking shifts between methods were quantified as the difference between the ranking of each alternative, while absolute ranking changes were used to assess the magnitude of positional variation. Mean and maximum absolute ranking shifts were calculated for each mixture to identify alternatives whose relative position was particularly sensitive to the selected assessment method. Such rank-based comparisons are relevant because changes in aggregation approaches and methodological assumptions may alter the relative ordering of alternatives [63].

Sensitivity was classified into four categories based on the absolute value of the maximum change, as follows:

- Very low ≤ 2 .
- Low: 3–5.
- Moderate: 6–10.
- High > 10 .

Second, a Monte Carlo analysis was performed to assess ranking robustness under simultaneous variability in the input parameters. The normalized compressive strength, carbonation rate, cost, and GWP values were independently perturbed within $\pm 20\%$ of their deterministic values using uniformly distributed random factors, $F \sim U(0.80, 1.20)$. A total of 1000 simulations were conducted, and the sustainability index and corresponding ranking of all mixtures were recalculated in each iteration. The resulting ranking distributions were summarized using the mean, median, best and worst ranks, as well as interquartile ranges.

4. Conclusions

Overall, this study confirms that the use of regionally available waste materials as partial replacements for cementitious materials and/or virgin aggregates can improve the sustainability performance of concrete. Mixtures containing recycled concrete aggregates and ash from local industries showed the best balance between mechanical performance, carbonation resistance, environmental impact, ecological cost, natural resource consumption, and material cost. However, the benefits of incorporating waste were not universal, as mixtures containing plastic waste or highly energy-demanding by-products and wastes may exhibit reduced compressive strength, durability, or environmental performance. The sustainability indices consistently identified 300/100RCAg, 300/10BA, and 407/10SCBA as the most favorable mixtures. Sensitivity and uncertainty analyses further showed that these mixtures generally maintained favorable positions in the classification regardless of the evaluation method, even when the input parameters varied by $\pm 20\%$, although some alternatives showed substantial changes in classification depending on the method. These findings highlight the potential of waste-based concrete to support recycling and circular economy strategies in the construction sector, while emphasizing the importance of integrated sustainability assessment and robustness analysis.

Author Contributions: Conceptualization, R.R.-R. and E.M.A.-G.; methodology, R.R.-R., M.A.-S. and W.M.-M.; software, R.R.-R. and M.A.N.-S.; validation, H.L.C.-G. and J.A.V.-P.; formal analysis, E.M.A.-G. and W.M.-M.; investigation, R.R.-R.; resources, E.M.A.-G.; writing—original draft preparation, R.R.-R.; writing—review and editing, W.M.-M. and M.A.-S.; visualization, M.A.N.-S., M.A.-S., J.A.V.-P. and H.L.C.-G.; supervision, E.M.A.-G. and W.M.-M.; project administration, E.M.A.-G., H.L.C.-G. and W.M.-M. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by the Coordinación de la Investigación Científica, Universidad Michoacana de San Nicolás de Hidalgo (CIC-UMSNH); Secretaría de Ciencia, Humanidades, Tecnología e Innovación (SECIHTI), through Frontier Science Group Project CF-2023-G-985 and Basic and Frontier Science Project for Consolidated Researchers CBF 2023-2024-1613; and Secretaría de Educación Pública-Programa para el Desarrollo Profesional Docente (SEP-PRODEP).

Data Availability Statement: The original contributions presented in this study are included in the article. Further inquiries can be directed to the corresponding authors.

Acknowledgments: The authors acknowledge the support of the Laboratorio de Materiales “Ing. Luis Silva Ruelas”, Facultad de Ingeniería Civil and Instituto de Ciencia, Tecnología e Innovación de Michoacán (Michoacán-ICTI).

Conflicts of Interest: The authors declare no conflicts of interest. The funders had no role in the design of the study; in the collection, analyses, or interpretation of data; in the writing of the manuscript; or in the decision to publish the results.

Abbreviations

The following abbreviations are used in this manuscript:

BA	Ash from local brick kilns
BMSP	Building Material Sustainability Potential
EASI	Empathetic Added Sustainability Index
SCM	Supplementary cementitious materials
SCBA	Sugarcane bagasse ash
GGBFS	Ground granulated blast furnace slag
AAS	Alkaline activated slag
C&DW	Construction and demolition waste
PET	Polyethylene terephthalate
S-LCA	Social life cycle assessment

GWP	Global warming potential
GER	Gross energy requirement
NRMC	Natural raw material consumption
RCA	Recycled concrete aggregate
W/C	Water/cement
f'c 28	Compressive strength at 28 days
KCO ₂	Carbonation rate

References

- Arreola-Sanchez, M.; Alonso-Guzman, E.M.; Martinez-Molina, W.; Torres-Acosta, A.A.; Chavez-Garcia, H.L.; Ponce-Ortega, J.M. Reinforced Concrete Structure Performance in Marine Structures: Analyzing Durability Indexes to Obtain More Accurate Corrosion Initiation Time Predictions. *Materials* **2021**, *14*, 7662. [CrossRef] [PubMed]
- World Economic Forum Desarrollo Sostenible. Available online: <https://www.weforum.org/stories/2024/09/cement-production-sustainable-concrete-co2-emissions/> (accessed on 2 August 2025).
- Global Cement and Concrete Association. *Futuro Concreto de La GCCA: Plan de Trabajo Hacia la Neutralidad en Carbono*; Global Cement and Concrete Association: London, UK, 2020.
- Global Cement and Concrete Association. *Futuro Del Hormigón*; Global Cement and Concrete Association: London, UK, 2021.
- Andrés, T.A.A. Sustainability Strategies for the Concrete Industry: A Holistic Perspective. In *Proceedings of the Life-Cycle Performance of Structures and Infrastructure Systems in Diverse Environments*; Li, C.-Q., Frangopol, D.M., Eds.; CRC Press Taylor & Francis Group: Boca Raton, FL, USA, 2025; pp. 261–268.
- Du, Y.; Korjakins, A.; Sinka, M.; Pundienė, I. Lifecycle Assessment and Multi-Parameter Optimization of Lightweight Cement Mortar with Nano Additives. *Materials* **2024**, *17*, 4434. [CrossRef] [PubMed]
- Martinez Molina, W.; Alonso Guzman, E.M.; Chavez Garcia, H.L.; Lara Gomez, C.; Gonzalez Valdez, F.M.; Torres Acosta, A.A.; Perez Quiroz, J.T.; Hernandez Barrios, H.; Martinez Alonso, W. Recycled Concrete, a Solution for Fine and Coarse Raw Material for New Concrete. In *Proceedings of the 2015 International Conference on Structural, Mechanical and Material Engineering*, Dalian, China, 6–8 November 2015.
- Jin, R.; Chen, Q. An Investigation of Current Status of “Green” Concrete in the Construction Industry. *ASC Annu. Int. Conf. Proc.* **2013**, *23*, 9.
- Suhendro, B. Toward Green Concrete for Better Sustainable Environment. In *Proceedings of the Procedia Engineering*; Elsevier B.V.: Amsterdam, The Netherlands, 2014; Volume 95, pp. 305–320.
- Liew, K.M.; Sojobi, A.O.; Zhang, L.W. Green Concrete: Prospects and Challenges. *Constr. Build. Mater.* **2017**, *156*, 1063–1095. [CrossRef]
- Ariza-Figueroa, H.A.; Croche, R.; Almeraya-Calderón, F.; Cabral, J.; Gaona-Tiburcio, C.; Ramírez-García, A.C.; Baltazar-Zamora, M.A. Estudio de La Durabilidad de Concretos Ternarios Con Ceniza de Bagazo de Caña de Azúcar y Humo de Sílice. In *Proceedings of the XV Congreso Latinoamericano de Patología de Construcción y XVII Congreso de Control de Calidad en la Construcción*; CONPAT: Chiapas, México, 2019.
- Chávez-García, J.J.; Alonso-Guzmán, E.M.; González-Luna, L.A.; Tafolla Martínez, E.; Báez-Ángel, V.M. Disminución de La Corrosión Mediante Una Adición Puzolánica Ecológica Para El Incremento de Durabilidad En Estructuras de Altas Especificaciones. In *Proceedings of the XV Congreso Latinoamericano de Patología de Construcción y XVII Congreso de Control de Calidad en la Construcción*; CONPAT: Chiapas, México, 2019.
- Gettu, R.; Patel, A.; Rath, V.; Prakasan, S.; Basavaraj, A.S.; Palaniappan, S.; Maity, S. Influence of Supplementary Cementitious Materials on the Sustainability Parameters of Cements and Concretes in the Indian Context. *Mater. Struct./Mater. Constr.* **2019**, *52*, 10. [CrossRef]
- Hrabová, K.; Lehner, P.; Ghosh, P.; Konečný, P.; Teplý, B. Sustainability Levels in Comparison with Mechanical Properties and Durability of Pumice High-Performance Concrete. *Appl. Sci.* **2021**, *11*, 4964. [CrossRef]
- Konečný, P.; Ghosh, P.; Hrabová, K.; Lehner, P.; Teplý, B. Effective Methodology of Sustainability Assessment of Concrete Mixtures. *Mater. Struct./Mater. Constr.* **2020**, *53*, 98. [CrossRef]
- Blancas-Herrera, V.H.; Martinez-Molina, W.; Chavez-Garcia, H.L.; Pacheco-Segovia, J.A.; Argüello-Hernandez, S.D.C.; Diaz-Gonzalez, N.; Cruz-Reyes, H.M.; Alonso-Guzman, E.M.; Ruiz, R.R. Evaluation of the Mechanical Strength of a Concrete Modified with Pet Fibers from Post-Consumer Bottles. *Key Eng. Mater.* **2020**, *862*, 66–71. [CrossRef]
- Alnahhal, M.F.; Alengaram, U.J.; Jumaat, M.Z.; Abutaha, F.; Alqedra, M.A.; Nayaka, R.R. Assessment on Engineering Properties and CO₂ Emissions of Recycled Aggregate Concrete Incorporating Waste Products as Supplements to Portland Cement. *J. Clean. Prod.* **2018**, *203*, 822–835. [CrossRef]

18. Alamin, A.; Samara, F.; Al-Tamimi, A.K. Environmental Risk Assessment of Sustainable Concrete Through the Chemical Composition of Metals and Polycyclic Aromatic Hydrocarbons. *Sustainability* **2024**, *16*, 9237. [\[CrossRef\]](#)
19. Sirico, A.; Bernardi, P.; Belletti, B.; Sciancalepore, C.; Milanese, D.; Paini, A.; Vignali, G. Environmental and Mechanical Analysis of Low-Carbon Concrete with Vitriified MSW Incineration Bottom Ash as Cement Replacement. *Struct. Concr.* **2024**, *25*, 2968–2990. [\[CrossRef\]](#)
20. Liu, J.C.; Hossain, M.U.; Ng, S.T.; Ye, H. High-Performance Green Concrete with High-Volume Natural Pozzolan: Mechanical, Carbon Emission and Cost Analysis. *J. Build. Eng.* **2023**, *68*, 106087. [\[CrossRef\]](#)
21. Soltanzadeh, F.; Behbahani, A.E.; Hosseinmostofi, K.; Teixeira, C.A. Assessment of the Sustainability of Fibre-Reinforced Concrete by Considering Both Environmental and Mechanical Properties. *Sustainability* **2022**, *14*, 6347. [\[CrossRef\]](#)
22. Naseri, H.; Jahanbakhsh, H.; Khezri, K.; Shirzadi Javid, A.A. Toward Sustainability in Optimizing the Fly Ash Concrete Mixture Ingredients by Introducing a New Prediction Algorithm. *Environ. Dev. Sustain.* **2022**, *24*, 2767–2803.
23. Pasana, A.S.; Loretero, M.E.; Giduquio, M.B. Use of Ground Glass Waste as Aggregate Filler in Concrete. *Nat. Environ. Pollut. Technol.* **2023**, *22*, 517–522. [\[CrossRef\]](#)
24. Martínez Molina, W.; Torres Acosta, A.A.; Alonso Guzmán, E.M.; Chávez García, H.L.; Hernández Barrios, H.; Lara Gómez, C.; Martínez Alonso, W.; Pérez Quiroz, J.T.; Bedolla Arroyo, J.A.; González Valdez, F.M. Concreto Reciclado: Una Revisión. *Alconpat* **2015**, *5*, 235–248. [\[CrossRef\]](#)
25. Bergman, T.L. Integrating Service-Life Modeling and Life-Cycle Assessment for Recycled-Aggregate Concrete. Master's Thesis, University of Colorado, Denver, CO, USA, 2015.
26. Valencia-Villegas, A.M.; González-Meza, A.M.; Arbeláez-Pérez, O.F. Evaluación de Las Propiedades Mecánicas de Concretos Modificados Con Microesferas de Vidrios y Residuos de Llantas. *Lámpsakos* **2019**, *22*, 16–26. [\[CrossRef\]](#)
27. De Schepper, M.; Van den Heede, P.; Van Driessche, I.; De Belie, N. Life Cycle Assessment of Completely Recyclable Concrete. *Materials* **2014**, *7*, 6010–6027. [\[CrossRef\]](#) [\[PubMed\]](#)
28. Ruiz-Ruiz, R.; Martínez-Molina, W.; Alonso-Guzmán, E.M.; Chávez-García, H.L.; Espino-González, C.U.; Arguello-Hernández, S.C.; Arreola-Sánchez, M. Comparación de Impactos Ambientales Entre Concreto Convencional y Reciclado Mediante ACV. Caso de Estudio: Concreto Con F'c de 35 MPa Elaborado Con Agregados de Morelia, Michoacán. In *Proceedings of the IX Congreso Nacional ALCONPAT*; ALCONPAT: Campeche, México, 2020.
29. Coffetti, D.; Crotti, E.; Gazzaniga, G.; Carrara, M.; Pastore, T.; Coppola, L. Pathways towards Sustainable Concrete. *Cem. Concr. Res.* **2022**, *154*, 106718. [\[CrossRef\]](#)
30. Václavík, V.; Ondová, M.; Dvorský, T.; Eštoková, A.; Fabiánová, M.; Gola, L. Sustainability Potential Evaluation of Concrete with Steel Slag Aggregates by the Lca Method. *Sustainability* **2020**, *12*, 9873. [\[CrossRef\]](#)
31. Bardan, M.; Czarnecki, L. Green Recycled Aggregate in Concrete: Feasibility Study. *Materials* **2025**, *18*, 488. [\[CrossRef\]](#) [\[PubMed\]](#)
32. Bai, J.; Ge, C.; Liang, J.; Xu, J. Recycled Aggregate: A Solution to Sustainable Concrete. *Materials* **2025**, *18*, 2706. [\[CrossRef\]](#) [\[PubMed\]](#)
33. Mel Fraga, J. Nuevo Modelo de Evaluación de La Sostenibilidad de Estructuras de Hormigón. Doctoral Dissertation, Universidad de Coruña, Coruña, Spain, 2017.
34. Berriel, S.S.; Díaz, Y.C.; Hernández, J.F.M.; Habert, G. Assessment of Sustainability of Low Carbon Cement in Cuba. Cement Pilot Production and Prospective Case. In *Calcined Clays for Sustainable Concrete: Proceedings of the 1st International Conference on Calcined Clays for Sustainable Concrete*; RILEM Bookseries; Springer: Dordrecht, The Netherlands, 2015; Volume 10. [\[CrossRef\]](#)
35. Gettu, R.; Pillai, R.G.; Santhanam, M.; Basavaraj, A.S.; Rathnarajan, S.; Dhanya, B.S. Sustainability-Based Decision Support Framework for Choosing Concrete Mixture Proportions. *Mater. Struct./Mater. Constr.* **2018**, *51*, 165. [\[CrossRef\]](#)
36. Hossain, M.U.; Poon, C.S.; Dong, Y.H.; Lo, I.M.C.; Cheng, J.C.P. Development of Social Sustainability Assessment Method and a Comparative Case Study on Assessing Recycled Construction Materials. *Int. J. Life Cycle Assess.* **2018**, *23*, 1654–1674. [\[CrossRef\]](#)
37. Coppola, L.; Coffetti, D.; Crotti, E.; Gazzaniga, G.; Pastore, T. An Empathetic Added Sustainability Index (EASI) for Cementitious Based Construction Materials. *J. Clean. Prod.* **2019**, *220*, 475–482. [\[CrossRef\]](#)
38. Mueller, H.S.; Haist, M.; Moffatt, J.S.; Vogel, M. Design, Material Properties and Structural Performance of Sustainable Concrete. *Procedia Eng.* **2017**, *171*, 22–32. [\[CrossRef\]](#)
39. Hafez, H.; Kurda, R.; Al-Ayish, N.; Garcia-Segura, T.; Cheung, W.M.; Nagaratnam, B. A Whole Life Cycle Performance-Based ECONomic and ECOlogical Assessment Framework (ECO2) for Concrete Sustainability. *J. Clean. Prod.* **2021**, *292*, 126060. [\[CrossRef\]](#)
40. Opon, J.; Henry, M. Implementation of a Multicriteria Analytical Framework for the Sustainability Evaluation and Comparison of Concrete Materials Considering Methodological Uncertainties. *J. Clean. Prod.* **2022**, *344*, 131057. [\[CrossRef\]](#)
41. Shinkhede, S.; Katore, V.; Joglekar, S.; Madurwar, M.; Mandavgane, S. Comparison of Different Concrete Compositions Based on Sustainability Score. *Int. J. Sustain. Eng.* **2021**, *14*, 2048–2059. [\[CrossRef\]](#)
42. Hrabova, K.; Teply, B.; Vymazal, T. Sustainability Assessment of Concrete Mixes. *IOP Conf. Ser. Earth Environ. Sci.* **2020**, *444*, 012021. [\[CrossRef\]](#)

43. Memon, S.A.; Javed, U.; Shah, M.I.; Hanif, A. Use of Processed Sugarcane Bagasse Ash in Concrete as Partial Replacement of Cement: Mechanical and Durability Properties. *Buildings* **2022**, *12*, 1769. [[CrossRef](#)]
44. Farrant, W.E.; Babafemi, A.J.; Kolawole, J.T.; Panda, B. Influence of Sugarcane Bagasse Ash and Silica Fume on the Mechanical and Durability Properties of Concrete. *Materials* **2022**, *15*, 3018. [[CrossRef](#)] [[PubMed](#)]
45. Coviello, C.G.; La Scala, A.; Sabbà, M.F.; Carnimeo, L. On the Cementitious Mixtures Reinforced with Waste Polyethylene Terephthalate. *Materials* **2024**, *17*, 5351. [[CrossRef](#)] [[PubMed](#)]
46. Cárdenas-Pulido, J.; Rodríguez-Loaiza, S.; Higuera Flórez, C. Evaluación Del Comportamiento a Compresión y Propiedades Físicas de Morteros de Cemento Reforzados Con Fibras Recicladas PET. *Sci. Tech.* **2020**, *25*, 269–279. [[CrossRef](#)]
47. Khatab, H.R.; Mohammed, S.J.; Hameed, L.A. Mechanical Properties of Concrete Contain Waste Fibers of Plastic Straps. *IOP Conf. Ser. Mater. Sci. Eng.* **2019**, *557*, 012059. [[CrossRef](#)]
48. Charco Ángel, D.L. Evaluación Por Durabilidad Del Concreto Modificado Con Fibras de PET y Polipropileno. Bachelor's Thesis, UMSNH, Morelia, Mexico, 2021.
49. Hernández Ferreyra, F.A. Evaluación Del Módulo de Ruptura Del Concreto Con Adición de PET y Polipropileno. Bachelor's Thesis, UMSNH, Morelia, Mexico, 2021.
50. Martínez González, A.D. Comportamiento Físico-Mecánico En Mezclas de Concreto Modificados Con Fibras de PET y Polipropileno. Bachelor's Thesis, UMSNH, Morelia, Mexico, 2021.
51. Blancas Herrera, V.H. Evaluación de Mezclas de Concreto Modificadas Con PET Reciclado y Adición Mineral. Su Influencia En El Módulo de Ruptura y En La Durabilidad de Pavimentos Rígidos. Master's Thesis, UMSNH, Morelia, Mexico, 2020.
52. González Castro, E. Mezcla de Concreto Hidráulico Con Ceniza de Bagazo de Caña Como Sustituto Del Cemento. Evaluación de Las Propiedades Físico-Mecánicas y de Durabilidad. Bachelor's Thesis, UMSNH, Morelia, Mexico, 2016.
53. García Romero, D. Evaluación de Mezclas de Concreto Hidráulico Con Sustituciones de Ceniza de Bagazo de Caña. Ceniza de Horno Agregado Reciclado a Edades Tardías Mediante Pruebas de Durabilidad. Bachelor's Thesis, UMSNH, Morelia, Mexico, 2021.
54. García Chávez, J.d.J. Adiciones Ecológicas Para Incrementar La Vida Útil de Obras de Infraestructura de Concreto Reforzado. Master's Thesis, UMSNH, Morelia, Mexico, 2019.
55. Contreras Flota, M.Á. Concreto Ecológico Elaborado a Partir de Desechos de Vidrio Como Sustituto Parcial de Los Agregados Finos y Gruesos. Master's Thesis, UMSNH, Morelia, Mexico, 2023.
56. NMX-C-515-ONNCCE-2016; Industria de La Construcción-Concreto Hidráulico-Durabilidad-Determinación de La Profundidad de Carbonatación En Concreto Hidráulico-Especificaciones y Método de Ensayo. Organismo Nacional de Normalización y Certificación de la Construcción y Edificación. CDMX: Mexico City, Mexico, 2016.
57. Hrabová, K.; Teplý, B.; Hájek, P. Concrete, Sustainability and Limit States. *IOP Conf. Ser. Earth Environ. Sci.* **2019**, *290*, 012049. [[CrossRef](#)]
58. NMX-C-530-ONNCCE-2018; Industria de La Construcción-Durabilidad-Norma General de Durabilidad de Estructuras de Concreto Reforzado-Criterios y Especificaciones. Organismo Nacional de Normalización y Certificación de la Construcción y Edificación. CDMX: Mexico City, Mexico, 2018.
59. Castro Borges, P.; Briceño Mena, J.A.; Torres Acosta, A.A. *Recomendaciones Generales Sobre Durabilidad*; ALCONPAT Internacional: Mérida, Mexico, 2020.
60. NMX-C-083-ONNCCE-2014; Industria de La Construcción-Concreto-Determinación de La Resistencia a Compresión de Especímenes-Método de Ensayo. Organismo Nacional de Normalización y Certificación de la Construcción y Edificación. CDMX: Mexico City, Mexico, 2014.
61. Liu, H.; Elchalakani, M.; Yehia, S.; Ali Sadakkathulla, M.; Xie, T.; Yang, B. The Influences of Metakaolin, w/b Ratio and Fibers on the Properties of Green-HFLWC. *Constr. Build. Mater.* **2022**, *361*, 129664. [[CrossRef](#)]
62. OECD/JRC. *Handbook on Constructing Composite Indicators*; OECD Publishing: Paris, France, 2008.
63. Triantaphyllou, E.; Sánchez, A. A Sensitivity Analysis Approach for Some Deterministic Multi-Criteria Decision-Making Methods. *Decis. Sci.* **1997**, *28*, 151–194. [[CrossRef](#)]

Disclaimer/Publisher's Note: The statements, opinions and data contained in all publications are solely those of the individual author(s) and contributor(s) and not of MDPI and/or the editor(s). MDPI and/or the editor(s) disclaim responsibility for any injury to people or property resulting from any ideas, methods, instructions or products referred to in the content.